CONSTANT NATURAL FREQUENCY PASSIVE-ACTIVE MOUNT

STATEMENT OF GOVERNMENT INTEREST

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

This invention relates to methods, apparatuses and systems for isolating vibrations emanating from sources such as machinery, more particularly to those which implement at least one resilient element and which provide support for such sources.

It is environmentally desirable in many contexts to reduce transmission of vibrations to neighboring structure. For example, the U.S.

Navy has an interest in attenuating the transmission, via connecting members to supporting structure, of unwanted vibrations from heavy machinery such as ship engines. Devices for reducing such transmission are generally known as vibration "isolators" because they serve to "isolate" the machine's vibration from contiguous structure. A vibration isolator is used to join one object to another and to restrict, to some degree, the transmission of vibration. See, e.g, J.E. Ruzicka, "Fundamental Concepts of Vibration Control," *Sound and Vibration*, July 1971, pp 16-23, incorporated herein by reference. See also, Eugene (Evgeny) I. Rivin, "Principles and Criteria of Vibration Isolation of Machinery," *ASME Journal of Mechanical Design*, Transactions of the ASME, Vol. 101, October 1979, pp 682-692, incorporated herein by reference. Both passive and active vibration isolation systems have been known in the art.

Passive vibration isolators have conventionally involved a passive damping arrangement which provides a resilient element ("spring") along with a damping mechanism ("energy releaser"), and which serves as a support ("mount"), for vibrating machinery or other structure. Passive vibration isolation devices, alternatively referred to as "mounts" or "springs" or "spring mounts" in nomenclature, operate on the principle of low dynamic load transmissibility by a material having a resilient property. Passive mounts are designated "passive" because their function

is based upon their inherent property rather than on their ability to, in an "active" manner, react to an in-situ condition.

Passive mounts have been known to use any of various materials for the resilient element, such as rubber, plastic, metal and air. Elastomeric mounts rely primarily upon the resilience and the damping properties of rubber-like material for isolating vibrations. Mechanical spring mounts implement a helical or other metal spring configuration. Pneumatic mounts utilize gas and an elastic material (such as reinforced rubber) as resilient elements in a bellows-like pneumatic spring assembly. A pneumatic mount or spring typically comprises a flexible member, which allows for motion, and a sealed pressure container or vessel having one or more compartments, which provides for filling and releasing a gas. Pneumatic springs are conventionally referred to as "air springs" because the gas is usually air. In conventional usage and as used herein the terms "air spring," "air mount" and "air spring mount" are used interchangeably, and in the context of these terms the word "air" means "gas" or "pneumatic," wherein "gas" or "pneumatic" refers to any gaseous substance.

Active vibration isolation has more recently become known in the art. Basically, a sensor measures the structure's vibration, an actuator is coupled with the structure, and a feedback loop tends to reduce the

unwanted motion. Typically, an output signal, proportional to a measurable motion (such as acceleration) of the structure, is produced by the sensor. Generally speaking, the actuator includes some type of reaction mass. A processor/controller processes the sensor-generated output signal so as to produce a control signal which drives the reaction mass, the actuator thereby producing a vibratory force, whereby the motion (e.g., acceleration) of the structure is reduced.

The three basic components of an active vibration isolation system are a motion sensor (e.g., a motion transducer), a processor/controller and a vibratory actuator. The sensor responds to vibratory motion by converting the vibratory motion into an electrical output signal that is functionally related to, e.g., proportional to, a parameter (e.g., displacement, velocity or acceleration) of the experienced motion. An accelerometer, for example, is a type of sensor wherein the output is a function of the acceleration input; the output is typically expressed in terms of voltage per unit of acceleration. The most common processor/controller is a "proportional-integral-derivative"-type ("PID"-type) controller, a kind of servomechanism, which proportionally scales, and integrates or differentiates, the sensor response. The actuator is essentially a device adapted to transmitting a vibratory force to a structure; such an actuator has been variously known and manifested as

an inertia actuator, inertial actuator, proof mass actuator, shaker, vibration exciter and vibration generator; as used herein, the terms "actuator," "inertia actuator" and "vibratory actuator" are interchangeable and refer to any of these devices. The actuator generates a force, applied to the structure, based on the electrical output signal from the processor/controller.

Incorporated herein by reference are the following two patents: Jen-Houne Hannsen Su U.S. Patent 5,899,443, issued 04 May 1999, entitled "Passive-Active Vibration Isolation"; and, Jen-Houne Hannsen Su U.S. Patent 5,887,858, issued 30 March 1999, entitled "Passive-Active Mount." Also incorporated herein by reference is Jen-Houne Hannsen Su, "Robust Passive-Active Mounts for Machinery and Equipment," *Proceedings of DETC '97*, 1997 ASME Design Engineering Technical Conferences, September 14-17, 1997, Sacramento, California (nine pages).

In Su '443 and Su '858, Su discloses inventions which uniquely and efficaciously combine known passive vibration technology with known active vibration technology. According to either Su '443 or Su '858, one or more vibratory actuators are coupled with (e.g., attached to or mounted upon) the bottom attachment plate of a conventional mount. Su '443 and Su '858 further disclose placement of one or more motion sensors (for sensing, e.g., velocity or acceleration) at the bottom attachment plate so

that the sensors and actuators are correlated in pairs, each sensor-actuator pair having one sensor and one actuator in a functionally and situationally propinquant relationship. The inventive mount disclosed in Su '443 and Su '858 is styled therein "passive-active" because, proceeding generally downward from the above-mount object to the below-mount foundation, the object's vibration is first reduced passively and then is further reduced actively.

Su '443 and Su '858 each teach the availing of active control so as to, in effect, increase the dynamic stiffness of the below-mount foundation. The impedance inherent in a realistic below-mount foundation falls short of the impedance inherent in an ideally rigid below-mount foundation. According to Su '443 and Su '858, the impedance differential between foundation reality and foundation ideality is largely compensated for by providing one or more inertia actuators on the bottom plate (e.g., retainer plate, mounting plate, backing plate, or end plate) of the mount, for example inside an air mount on its bottom plate.

Su '443 and Su '858 thus provide more effective, yet practical and affordable, vibration isolation methods, apparatuses and systems. Typically, the electronic components will be commercially available; the sensors, actuators and PID-type controllers appropriate for most inventive embodiments according to Su '443 and Su '858 will be "off-the-shelf" items

which can be purchased at less than prohibitive costs. In accordance with Su '443 and Su '858, the sensors and actuators can be retrofitted in existing conventional mounts, or the inventive mount can be manufactured or assembled from scratch.

For many applications according to Su '443 and Su '858, the inventive mount will afford superior performance in isolating vibrations of an above-mount structure from a realistic below-mount foundation; for some applications, however, the inventive mount according to Su '443 and Su '858 can be used quite effectively for isolating vibrations of a below-mount foundation from an above-mount structure such as a piece of equipment. For applications involving heavy machinery, a multiplicity of inventive mounts can be utilized. For a single piece of heavy machinery, vibration isolation effectiveness can be expected to increase in accordance with an increase in the number of inventive mounts that are used.

The active vibration control aspect of the inventions disclosed by Su '443 and Su '858 serves to enhance the passive vibration control aspect of these inventions. The inventions of Su '443 and Su '858 are "fail-safe" in a sense; in the event of inoperability of an inventive mount according to Su '443 and Su '858 (e.g., due to power failure or electromechanical failure), the performance of such inventive mount degrades to that of the conventional passive mount.

The inventions according to Su '443 and Su '858 typically obviate the need to fortify, for isolation purposes, the existing below-mount foundation. The foundation will be less expensive, since its design will involve only considerations concerning load-carrying capacity (e.g., static strength/structural integrity). Vibration-related considerations will not need to be addressed in foundation design; such factors as fatigue life, vibration and noise will be controlled automatically by the advanced mount according to Su '443 and Su '858.

Active control according to both Su '443 and Su '858 typically serves to complement the deficiency of the passive control in the low frequency. Conventional passive mounts are generally characterized by low frequency enhancement; conventional passive mounts typically have inherent low frequency resonance, and consequently may be ineffective or may even cause enhancement of dynamic load transmission at low frequency. In inventive practice according to Su '443 and Su '858, the low frequency disturbance enhancement due to the resonance frequency of the mounts should be more or less reduced, depending on the force output capacity of the actuators used for a given inventive embodiment.

Notwithstanding the significant advantages generally associated with practice of inventive vibration isolation according to Su '443 and Su '858, such practice according to Su '443 and Su '858 may be less than

entirely satisfactory for certain applications. In particular, typical inventive embodiments according to Su '443 and Su '858 are suitable for a rather limited scope of isolation loading; that is, in effecting vibration isolation, a typical apparatus according to Su '443 or Su '858 is designed to be subjected to a relatively narrow range of weight, albeit the apparatus is highly effective for such purposes. Nevertheless, it is sometimes desirable to utilize vibration isolation apparatus which is applicable to a relatively broader scope of isolation loading -- that is, to a relatively wide range of weight to which the apparatus is to be subjected in effecting vibration isolation.

SUMMARY OF THE INVENTION

In view of the foregoing, it is an object of the present invention to provide method, apparatus and system for highly effective vibration isolation.

It is another object of this invention to provide method, apparatus and system for accomplishing same in association with a wide range of loads.

A further object of this invention is to provide such method,

apparatus and system which are practical, relatively uncomplicated and cost-effective for many applications.

The present invention provides apparatus, system and method for vibration isolation, especially for reducing transmission of vibration of an object to a foundation for said object. Certain principles pertaining to the present invention's passive-active elastomeric/viscoelastic isolator (mount) are the same as or similar to those pertaining to the passive-active air mount disclosed by Su '443 and Su '858. Notably and contradistinctively, however, the passive-active mount according to this invention is a "*constant natural frequency*" (abbreviated herein, "CNF") passive-active mount. The CNF passive-active mount according to this invention affords wide load range application and simple implementation. The present invention's passive vibration control is effectuated by one or more "streamlined resilient elements," each attributed with a "constant natural frequency" (CNF) quality whereby such element is naturally predisposed to passively reducing vibration at a particular frequency band regardless of the extent of the loading, within certain parameters, to which such element is being subjected. The CNF-endowed passive vibration control represents a significant improvement vis-a-vis' Su '443 and Su '858.

Regis V. Schmitt and Matthew L. Kerr, "A New Elastomeric Suspension Spring," Society of Automotive Engineers (SAE), Inc., SAE

Paper No. 710058, *Automotive Engineering Congress*, Detroit, Michigan, January 11-15, 1971 (8 pages), incorporated herein by reference, disclose a constant natural frequency spherical elastomeric spring element. Schmitt et al. teach (Schmitt et al., first page) the advantageousness of "maintaining a constant natural frequency, on the primary suspension spring, with varying vehicle weight." A constant natural frequency is seen by Schmitt et al. as capable of "providing consistent ride quality with varying vehicle weight." As explained by Schmitt et al., "Natural frequency is a function of spring rate and supported mass. Thus, it changes as supported mass changes if spring rate is a constant (linear spring). The contribution of a linear, or nearly linear, primary suspension spring to natural frequency changes with vehicle weight. This results in a compromise which gives best performance over only a part of the total range of truck weight expected."

Schmitt et al. (Schmitt et al., third page) tested a spherical elastomeric sample and found that it "does, in fact, have a constant frequency characteristic." They further found "that, in the spherical spring, natural frequency is dependent on the size of the sphere and not on compound stiffness. Increasing compound stiffness (durometer) decreases the actual sphere deflection for a given load. The spring rate, hence natural frequency, for that load depends on the slope of the load deflection

curve at the point reached by that load. The shape of the load deflection curve and its slope for a given load is dependent on the size of the sphere and not on compound stiffness." In addition to a spherically shaped elastomeric sample, they tested elastomeric samples having "hourglass" and "truncated" shapes.

Eugene (Evgeny) I. Rivin, "Passive Engine Mounts -- Some Directions for Further Development," *SAE 1985 Transactions*, Society of Automotive Engineers (SAE), Inc., SAE Paper No. 850481, Section 3, Vol. 94, 1986, pp. 3.582-3.591, incorporated herein by reference, discloses that "[a] constant natural frequency (CNF) mount is characterized by a specific nonlinear load-deflection characteristic when its vertical stiffness k_Z is proportional to the applied weight load W, $k_Z = AW$. Accordingly, vertical (bounce) natural frequency f_Z is [constant]. To be a truly CNF mount, its spring rates in the x and y directions must also be proportional to W, or ratios k_Z/k_X and k_Z/k_Y must be constant while the weight load varies in its rated range"

Rivin (1985) teaches that CNF "mounts have several advantages, whose relative importance depends on the goals to be achieved. If decoupling is considered as an important goal, it can be much more reliably achieved by using CNF mounts.... Another unique advantage of the CNF mount is its insensitivity to rubber durometer variations.... If the

rubber durometer deviates into lower values,... the natural frequency for a given weight load in the linear range becomes smaller. However, the natural frequency in the CNF range stays the same, although the range starts from a smaller weight load.... A similar effect occurs for a higher-than-nominal durometer.... In this case the natural frequency for a given weight load in the linear range becomes higher...., but the natural frequency in the CNF range is still the same."

Eugene (Evgeny) I. Rivin, "Vibration Isolation of Precision Equipment," *Precision Engineering*, 1995, vol. 17, pp 41-56, incorporated herein by reference, discloses (e.g., Rivin, 1995, p 55) the "use of constant-natural-frequency (CNF) isolators, in which stiffness in both vertical and horizontal directions is proportional to the weight load on the isolator. As a result, such isolators provide a high degree of dynamic decoupling without the need to determine the center-of-gravity position, to calculate weight load distribution between the mounting points, etc. In addition to this, such isolators have a significantly reduced sensitivity to manufacturing tolerances."

Eugene (Evgeny) I. Rivin, "Shaped Elastomeric Components for Vibration Control Devices," *Sound and Vibration*, July 1999, Vol. 33, no. 7, pp 18-23, incorporated herein by reference, teaches (Rivin, 1999, p 21) that "[p]erformance of vibration isolators improves significantly if the

isolator has a special nonlinear load-deflection characteristic whereas its stiffness is proportional to weight load on the isolator within a relatively broad load range (constant natural frequency or CNF characteristic)." Rivin discloses spheres, radially loaded cylinders and radially loaded toruses as examples of "shaped elastomeric components." It is taught by Rivin that the "use of shaped elastomeric components results in much more compact designs due to larger allowable compression deformations under static loads. Larger compression deformations can be allowed due to a much more uniform stress distribution and lower maximum stresses/strains and lower creep rates as compared with conventional bonded rubber blocks made of the same rubber blend. In addition to these important advantages, it has been shown that the CNF isolators have a substantially lower sensitivity to production variations of rubber hardness than conventional isolators with linear load-deflection characteristics, resulting in much better performance uniformity. Thus, use of radially loaded rubber cylinders/toruses could significantly advance the state of the art for vibration isolators. Spherical rubber elements have the same advantages (constant natural frequency in a relatively broad load range and reduced creep) and can be used for lightly loaded vibration isolators."

Evgeny I. Rivin U.S. Patent 5,934,653, entitled "Nonlinear Flexible Connectors with Streamlined Resilient Elements" and issued 10 August

1999, is hereby incorporated herein by reference. Rivin '653 discloses a streamlined elastomeric (e.g., rubber) resilient element characterized by nonlinear load deflection. Disclosed by Rivin '653 (e.g., Rivin '653, col. 2) is "the use of streamlined rubber elements such as balls, ellipsoids, toruses, radially-loaded cylinders, etc." According to Rivin '653, such streamlined resilient elements are characterized by significant (e.g., two to three times) increase in the allowable continuous compression deformation, and are further characterized by a progressively nonlinear deformation. Rivin '653 teaches the desirability of "utilizing streamlined resilient elements without compromising their special deformation properties, which may be caused by their bonding to other elements."

The following U.S. patents, each of which is incorporated herein by reference, are also of note: Houghton, Jr. et al. U.S. Patent 6,209,841 B1 issued 03 April 2001; Krysinsky et al. U.S. Patent 6,045,090 issued 04 Apr. 2000; Lee et al. U.S. Patent 5,780,948 issued 14 July 1998; Lee et al. U.S. Patent 5,780,740 issued 14 July 1998; Rivin U.S. Patent 5,630,758 issued 20 May 1997; Cheng et al. U.S. Patent 5,544,451 issued 13 Aug. 1996; Leyshon U.S. Patent 5,016,862 issued 21 May 1991; Hall et al. U.S. Patent 4,880,201 issued 14 Nov. 1989; Lafferty U.S. Patent 4,619,467 issued 28 Oct. 1986; Shtarkman U.S. Patent 4,509,730 issued 09 April 1985; Stone et al. U.S. Patent 4,452,329 issued 05 June 1984; Barley U.S. Patent

4,384,701 issued 24 May 1983; Madden U.S. Patent 4,218,187 issued 19 Aug. 1980; Leingang U.S. Patent 3,997,151 issued 14 Dec. 1976; Taylor U.S. Patent 3,947,004 issued 30 March 1976.

The present invention uniquely features the utilization of one or more shaped elastomeric (e.g., viscoelastic) elements (e.g., members) in order to increase the load range applicability of the "passive" aspect of a passive-active mount such as disclosed by Su '443 and Su '858. These shaped or contoured elastomeric (e.g., viscoelastic) elements are referred to herein as "streamlined resilient elements." Typically, a CNF passive-active mount according to this invention will be uniquely characterized by a specific arrangement of one or more streamlined resilient elements along with one or more inertial actuators. The present invention's CNF passive-active mount affords wide load range application and simple implementation.

Since the streamlined resilient element or elements maintain approximately the same mount resonance frequency for a wide range of isolation weight, the mount according to this invention is termed a "constant natural frequency passive-active mount" (or, abbreviatedly, a "CNF passive-active mount"). At least one streamlined resilient element tends to impart a constant natural frequency (CNF) attribute to the inventive passive-active mount. Accordingly, the term "streamlined

resilient element," as used herein, refers to any elastomeric (e.g., viscoelastic) object which has this kind of CNF-attributive quality when used in the context of vibration isolation. Because of its CNF-attributive quality, a streamlined resilient element" is also variously and synonymously referred to herein as a "constant natural frequency element," or a "CNF element," or "a streamlined CNF element," or a "resilient CNF element," or a "streamlined resilient CNF element."

Generally, a "streamlined resilient element" will be characterized by a so-called "streamlined" shape, such as but not limited to that which describes one or more of the following: a spherical shape; a prolate spheroid (e.g., ellipsoid) shape adaptable to loading in either the short-axial or long-axial direction; a cross-sectionally circular segmented toroidal (doughnut) shape (e.g., a section of a cross-sectionally circular torus) adaptable to radial loading; a cross-sectionally noncircular (oval, e.g., elliptical) segmented toroidal (doughnut) shape (e.g., a section of a cross-sectionally oval torus) adaptable to radial loading; a cross-sectionally circular cylindrical shape adaptable to radial loading; a cross-sectionally noncircular (oval, e.g., elliptical) cylindrical shape adaptable to radial loading; a cross-sectionally circular disk shape (which, actually, is an axially-longitudinally short form of a cylindrical shape) adaptable to radial loading; a cross-sectionally noncircular (oval, e.g., elliptical) disk shape

(which, actually, is an axially-longitudinally short form of a cylindrical shape) adaptable to radial loading; a cross-sectionally circular toroidal (doughnut) shape adaptable to radial loading; a cross-sectionally noncircular (oval, e.g., elliptical) toroidal (doughnut) shape adaptable to radial loading; a toroidal shape, adaptable to radial loading, having a longitudinal (circumferential) axis of symmetry which defines a circular shape; a toroidal shape, adaptable to radial loading, having a longitudinal (circumferential) axis of symmetry which defines a noncircular (oval, e.g., elliptical) shape; a segmented toroidal shape, adaptable to radial loading, having a longitudinal axis of symmetry which defines a segment of a circular shape; a segmented toroidal shape, adaptable to radial loading, having a longitudinal axis of symmetry which defines a segment of a noncircular (oval, e.g., elliptical) shape; any truncated (e.g., flattened) version of any of the aforementioned shapes.

Generally, a streamlined resilient element will be at least substantially characterized by a curvilinear profile (such profile lying in an imaginary plane through the end plates and perpendicular thereto) which describes either a circular shape or a non-circular shape such as an oval. According to frequent inventive practice, the streamlined resilient element is truncated at one or both ends, perhaps for the purpose of facilitating coupling of the streamlined resilient element with the end plates, and

perhaps alternatively or additionally for the purpose of enhancing vibration isolation characteristics of the inventive mount. A streamlined resilient element which is truncated at either or both ends approximately or substantially defines the shape which would exist in the absence of such truncation.

According to typical embodiments of the present invention, there are two securement members connected, on opposite sides or ends, with the streamlined resilient element. The inventive CNF passive-active mount represents the "isolator" entity. The mount includes two securement members, viz., an "isolatee-entity-securement" member and an "isolated-entity-securement" member. The mount's "isolatee-entity-securement" member is the mount's securement member which is attached to, or is attached with respect to, the "isolatee" entity. The "isolatee" entity is the entity from which the "isolated" entity's vibrations are sought to be isolated. Another securement member of the mount, viz., the "isolated-entity-securement" member, is attached to, or is attached with respect to, the isolated entity. For most inventive embodiments, the isolated entity is an object (such as a machine) and the isolatee entity is a "foundation" for the object. An important benefit of the present invention is its applicability to a wide range of masses (or weights) of the isolated entity.

Typically in accordance with this invention, each actuator has a

companion sensor. Each sensor responds to a local vibratory motion of the mount's isolatee-entity-securement member by sending a sensor feedback signal to a signal processor, which in turn sends a command signal to the sensor's companion actuator, which in turn exerts or imparts a vibratory control force or motion upon the mount's isolatee-entity-securement member. Each sensor continuously responds to the local vibration of the isolatee-entity-securement member, and the feedback loop inclusive of that sensor thus perpetuates. Each independent active vibration control subsystem includes a sensor and its corresponding actuator. The cumulative active vibration control system includes all of the individual active vibration control subsystems, each of which is uncomplicated.

When used herein adjectively to modify an inventive mount's securement member, the words "upper," "top," "lower" and "bottom" are terms of convenience which are intended to suggest structural and functional contradistinction rather than relative spatial positioning. Hence, in such contexts, the terms "upper" and "top" refer to isolatee entity securement, i.e., securement of the mount with respect to the isolated entity, e.g., a vibrating object; the terms "lower" and "bottom" refer to isolated entity securement, i.e., securement of the mount with respect to the isolatee entity, e.g., a foundation for the vibrating object.

Typical inventive embodiments, in application, effectuate a

"localized" vibration control approach rather than a "global" vibration control approach. Incorporated herein by reference is Su, Jen-Houne Hannsen Su et al., "Mechanisms of Localized Vibration Control in Complex Structures," *Journal of Vibration and Acoustics*, January 1996, Volume 118, pages 135-139. This paper is instructive regarding localized vibration control, which involves stabilization in localized areas of a structure, as distinguished from global vibration control, which involves stabilization of the entire structure.

Most active vibration control research, particularly in space structures applications, has dealt with controlling vibration in a global sense; the controller stabilizes the entire structure. When the interest lies in stabilizing only certain localized areas of the structure, the control objective can be focused and actuators/sensors are generally required only in the "control areas." This localized control approach can provide more effective vibration suppression in the control areas, and can require fewer actuators and sensors compared to global vibration control. Deciding where to mount sensors and actuators is somewhat simpler in a localized vibration control problem than in a general vibration control problem. For localized vibration control, sensors and actuators are usually located within the control areas, which usually represent together a relatively small portion of the entire structure.

A typical inventive vibration isolator according to this invention is adapted for engagement with a processor/controller (e.g., PID-type controller) which is capable of generating a control signal. The vibration isolator comprises a spring assembly, at least one sensor and at least one actuator. The spring assembly includes a top member (for securing the spring assembly with respect to an isolated entity), a bottom member and at least one interposed streamlined resilient element. The top member (typically a plate-type structure) is for securing the spring assembly with respect to an isolated entity. The bottom member (typically a plate-type structure) is for securing the spring assembly with respect to an isolatee entity (e.g., the foundation). Each streamlined resilient element is characterized by an approximately constant natural frequency (CNF) regardless of the loading imposed within a particular range of loading (e.g., weight).

Each streamlined resilient element is at least substantially composed of an elastomeric material and at least substantially has a contoured shape having CNF properties, such as spheroidal, prolate spheroidal, circular cylindrical, noncircular cylindrical, torroidal and torroidal segment. A disk is a kind of cylinder; the term "disk," as used herein, is a descriptive term for a cylinder characterized by a short axial length relative to its diameter. Each streamlined resilient element has the

property of passively reducing vibration within a "special passive-reduction-related frequency bandwidth" which is at least substantially constant when the streamlined resilient element is subjected to a wide range in terms of the degree of loading. Cumulatively speaking, the one or more streamlined resilient elements are thereby capable, in net effect, of passively reducing vibration within a "general passive-reduction-related frequency bandwidth" which is at least substantially constant when the one or more streamlined resilient elements are subjected to a wide range in terms of the degree of loading which is associated with the isolated entity and/or the isolatee entity. According to typical inventive embodiments, the "general passive-reduction-related bandwidth" is approximately commensurate with the "special passive-reduction-related bandwidth."

It is believed by the inventors that a streamlined resilient element has constant natural frequency attributes essentially because of the "streamlined" shape and the material resiliency (or elasticity) of the streamlined resilient element. In inventive operation, as higher load is applied with respect to the streamlined resilient element (i.e., the passive component), more material of the streamlined resilient element will come in contact with the attachment plates. Increased contact will render the streamlined resilient element stiffer, thereby maintaining the ratio of

stiffness (spring rate) to load.

The one or more sensors, the one or more actuators and the processor-controller with which the inventive isolator is engaged represent components of a feedback loop system. Each sensor is coupled with the bottom member and is capable of generating a sensor signal which is in accordance with the vibration in a local zone of interest in the bottom member. Each actuator is coupled with the bottom member and is collocationally paired with one sensor so as to share approximate coincidence with respect to both physical situation and operational direction. Each actuator is capable of generating, in the local zone of interest of the sensor with which the actuator is collocationally paired, a vibratory force which is in accordance with the control signal which is generated by the processor/controller. The control signal is in accordance with the sensor signal which is generated by the sensor with which the actuator is collocationally paired. The vibratory force which is generated by an actuator has the tendency of actively reducing vibration within an "active-reduction-related frequency bandwidth" which differs from the "general passive-reduction-related bandwidth."

Many embodiments of this invention implement a single sensor/actuator unit and a plurality of streamlined resilient members; typically, according to such embodiments, the collocated sensor/actuator

unit is centrally located on the bottom plate, while the streamlined resilient members are peripherally located on the bottom plate. For such embodiments, the inventive feedback loop system will usually include a single feedback loop system. Other inventive embodiments implement a plurality of sensor/actuator units and at least one streamlined resilient member; typically, according to such embodiments, each streamlined resilient member will be centrally located on the bottom plate, while each of the plural sensor/actuator units will be peripherally located thereon, typically in symmetrical fashion about the center thereof. For such embodiments, the inventive feedback loop system will include a plurality of feedback loop subsystems. Generally, in inventive practice, the desired numbers, sizes, shapes and arrangements of the at least one streamlined resilient member and the at least one sensor/actuator unit will at least to some extent depend on the overall size and shape of the inventive constant natural frequency (CNF) mount and the force output capacity of the actuators selected.

An inventive configuration involving a single, centrally located sensor/actuator unit and plural, peripherally located streamlined resilient members may be preferable for many applications, due at least to greater compactness vis-a-vis' other inventive configurations. For instance, an inventive configuration involving more than one centrally located

sensor/actuator unit will generally take up more space than will an inventive configuration involving one centrally located sensor/actuator unit. Similarly, with regard to inventive embodiments wherein at least one streamlined resilient member is centrally located and at least two sensor/actuator units are peripherally located, an inventive configuration involving more than one centrally located streamlined resilient member will generally take up more space than will an inventive configuration involving one centrally located streamlined resilient member.

Regardless of whether one or more sensor/actuator units is inventively employed, each sensor is coupled with the bottom plate and generates a sensor output signal which is a function of the localized vibration of the bottom plate. The PID-type controller generates at least one control signal, each control signal being a function of its collocated sensor signal. Each actuator is coupled with the bottom plate above the bottom plate, wherein the sensors and actuators are in one-to-one correspondence; that is, each actuator is located proximate the corresponding sensor and generates a vibratory force which is a function of the control signal which is a function of the sensor signal generated by the corresponding sensor. Each feedback loop system or subsystem will include a sensor and an actuator, correlatively paired.

For many inventive embodiments it is preferred that each sensor-

actuator unit (sensor-to-actuator correlation) include "collocation" of the sensor and the corresponding actuator; i.e., each collocated sensor-actuator pair is positioned in a kind of spatial and vectorial alignment, whereby the sensing of the sensor and the actuation of its corresponding actuator are approximately in the same direction. For some such inventive embodiments having at least two sensors and at least two actuators, all the collocational directions preferably are approximately parallel.

Some inventive embodiments manifesting collocational parallelism preferably manifest a kind of symmetry which may serve to optimize, perhaps even synergistically, the overall effectiveness of the individual localized active vibration control system or subsystems. For typical such embodiments, the centrally located entity or entities (whether this be at least one streamlined flexible member or at least one sensor/actuator unit) are characterized by a centric imaginary axis which is approximately vertical (i.e., approximately perpendicular to the bottom plate). This centric imaginary axis is approximately coincident with or approximately parallel to the approximately vertical (i.e., approximately perpendicular to the bottom plate) collocational direction of each sensor/actuator unit, as well as to the approximately vertical (i.e., approximately perpendicular to the bottom plate) imaginary axis of at least substantial symmetry of each streamlined flexible member. Every arrangement of the at least one

sensor/actuator unit, in terms of their respective collocational directions, is characterized by approximate symmetry with respect to the centric axis. Similarly, every arrangement of the at least one streamlined flexible member, in terms of their respective axes of symmetry, is characterized by approximate symmetry with respect to the centric axis. Further, the top and bottom plates are typically congruous with each other so that their respective perimeters are also characterized by approximate symmetry with respect to the centric axis.

Typically, both the top (upper) and bottom (lower) members used for securing a conventional air mount are flat structures, e.g., plates. For illustrative purposes, the top and bottom plates are exemplified herein as each having a rectangular (in particular, a square) shape; nevertheless, in the light of this disclosure, it will be understood by the ordinarily skilled artisan that, in inventive practice, the top and bottom plates can each describe practically any shape, and that such shapes can differ from each other (e.g.., they need not be comparable or similar). Generally in practicing the present invention, the lower plate's upper surface will be available for inventive sensor-actuator implementation in combination with streamlined flexible member implementation.

The present invention features the utilization of one or more streamlined resilient elements. Any number, shape or combination of

shapes of discrete (e.g., segmented) streamlined resilient elements is possible in accordance with the present invention. The CNF passive-active mount in accordance with the present invention can be used for a wide range of vibration isolation weight. The inventive mount is typically feasible for load ranges between as high as ten times to one hundred times the minimum load. In other words, generally speaking, the present invention's CNF passive-active mount can operate in inventively appropriate CNF fashion in a load range which is extends between the minimum load and some large multiple thereof. According to some inventive embodiments, the load range is between the minimum load and ten times the minimum load. According to other inventive embodiments, the load range is between the minimum load and one hundred times the minimum load. According to most inventive embodiments, the load range will be between the minimum load value and a multiple load value of the minimum load value, wherein the multiple load value is between ten times and one hundred times the minimum load value. That is to say, the wide (broad) range of loading, in terms of the degree of loading which at least substantially results from at least one of said isolated entity and said isolatee entity, is an approximate range which is between a minimum loading value and a maximum loading value; the maximum loading value is between about ten times and about one hundred times the minimum

loading value.

Yet, the inventive mount typically is substantially smaller than the conventional mount designs which would seek to accomplish vibration isolation over broad loading ranges. Since each inventive CNF passive-active mount achieves vibration isolation over a broad loading range, a smaller inventory of inventive mounts will suffice for many purposes. Moreover, the typical inventive mount is characterized by lower heat generation than characterized conventional mounts. Many inventive embodiments are configured so as to provide good heat ventilation for the active component (e.g., the component which includes at least one collocated actuator/sensor pair). The same or similar inventive CNF passive-active mount design can be used at different locations or on different types of foundations. The present invention has a simple non-pneumatic design which advantageously admits of easy fabrication. Furthermore, the typical inventive mount has snubbing/captive capability for shock control.

Other objects, advantages and features of this invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the present invention may be clearly understood, it will now be described, by way of example, with reference to the accompanying drawings, wherein like numbers indicate the same or similar components, and wherein:

FIG. 1 is a diagrammatic perspective view of an embodiment of a CNF passive-active mount in accordance with the present invention, wherein one sensor/actuator unit is centrally situated and four approximately circular disk-shaped streamlined resilient elements are peripherally situated. For illustrative purposes, the upper plate is shown to be slightly separated (raised) from the streamlined resilient elements.

FIG. 2 is a diagrammatic top plan view, sans upper plate and partially in section, of the inventive embodiment shown in **FIG. 1**.

FIG. 3 is a diagrammatic elevation view, partially in section, of the inventive embodiment shown in **FIG. 1**.

FIG. 4 is a photographic perspective view of a prototypical embodiment of an inventive CNF passive-active mount, such prototypical embodiment being similar to the embodiment shown in **FIG. 1**, wherein the streamlined resilient elements are oblong and are characterized by

oppositely sided flattened edges (truncations) for facilitating attachment to the upper and lower plates. The upper plate is removed from this view for illustrative purposes.

FIG. 5 is a diagrammatic perspective view of another embodiment of a CNF passive-active mount in accordance with the present invention, wherein one sensor/actuator unit is centrally situated and four streamlined resilient elements, approximately shaped like one-quarter segments of a torus (i.e., a "doughnut," or an annular, tubular ring), are peripherally situated. For illustrative purposes, the upper plate is shown to be slightly separated from the streamlined resilient elements.

FIG. 6 is a diagrammatic elevation view, partially in section, of another embodiment of a CNF passive-active mount in accordance with the present invention, wherein one approximately spherical (with diameter comparable to the length / width of the attachment plates) streamlined resilient element is centrally situated and (at least) two sensor/actuator units are peripherally situated.

FIG. 7 is a diagrammatic elevation view, partially in section, of another embodiment of a CNF passive-active mount in accordance with the present invention, wherein three or more approximately circularly disk-shaped streamlined resilient elements are centrally situated and (at least) two sensor/actuator units are peripherally situated.

FIG. 8 is a diagrammatic elevation view, partially in section, of another embodiment of a CNF passive-active mount in accordance with the present invention, wherein one approximately oval-shaped streamlined resilient element is medially situated, at least two approximately oval-shaped streamlined resilient elements are peripherally situated, and (at least) two sensor/actuator units are intermediately situated (intermediate the medial streamlined resilient element and a peripheral streamlined resilient element).

FIG. 9 is a diagrammatic perspective view, partially in section, of an embodiment of a streamlined resilient element which is shaped like a torus segment but which is truncated top and bottom.

FIG. 10 is a diagrammatic perspective view, partially in section, of an embodiment of a streamlined resilient element which is shaped like a cylindrical section but which is truncated top and bottom.

FIG. 11 is a diagrammatic elevation view of an embodiment of a streamlined resilient element which is circular in profile, particularly illustrating both a truncated form and a non-truncated form thereof.

FIG. 12 is a diagrammatic elevation view of an embodiment of a streamlined resilient element which is oval in profile, and which is adaptable to being coupled with end plates which are approximately parallel to the longitudinal axis of the streamlined resilient element,

particularly illustrating both a truncated form and a non-truncated form thereof.

FIG. 13 is a diagrammatic elevation view of an embodiment of a streamlined resilient element which is oval in profile, and which is adaptable to being coupled with end plates which are approximately perpendicular to the longitudinal axis of the streamlined resilient element, particularly illustrating both a truncated form and a non-truncated form thereof.

FIG. 14 is a diagrammatic elevation view similar to the view shown in **FIG. 11**, wherein the inventive embodiment shown of a streamlined resilient element which is circular in profile is nontruncated at the top but truncated at the bottom.

FIG. 15 is a simplified block diagram of each active subsystem control loop for an embodiment of a vibration isolation system in accordance with the present invention.

FIG. 16 is a graphical representation of the load-deflection curves, in terms of force (pounds) versus displacement (inches), which were ascertained for eight prototypical versions of the prototypical inventive embodiment shown in **FIG. 4**, wherein the eight prototypical versions were characterized by various combinations of three parameters (viz., lengthwise diameter in inches, thickness in inches, and durometer

number) pertaining to each of the four streamlined resilient elements. The prototypical inventive embodiment shown in **FIG. 4**, which represents one of these eight prototypical versions, has a lengthwise diameter of 2.5 inches, a thickness of 0.75 inches, and a durometer number of 40.

FIG. 17 is a photographic perspective view of a demonstration test rig which was used in association with the prototypical inventive embodiment shown in **FIG. 4**.

FIG. 18 is a graphical representation of the disturbance force from the shaker in terms of weight (pounds) versus frequency (Hz). This graph is based on disturbance force data which were obtained during inventive testing, using the demonstration test rig shown in **FIG. 17**, of the prototypical inventive embodiment shown in **FIG. 4**.

FIG. 19 is a graphical representation of the acceleration, in terms of dB per g versus frequency (Hz), which existed below the inventive CNF passive-active mount and closer to the foundation support. This graph is based on acceleration data which were obtained during inventive testing, using the demonstration test rig shown in **FIG. 17**, of the prototypical inventive embodiment shown in **FIG. 4**.

FIG. 20 is a graphical representation of the acceleration, in terms of dB per g versus frequency (Hz), which existed below the inventive CNF passive-active mount and closer to the free end (the end opposite the

foundation support). This graph is based on acceleration data which were obtained during inventive testing, using the demonstration test rig shown in **FIG. 17**, of the prototypical inventive embodiment shown in **FIG. 4**.

FIG. 21 is a graphical representation of the required current per actuator, in terms of amperes versus frequency (Hz). This graph is based on current data which were obtained during inventive testing, using the demonstration test rig shown in **FIG. 17**, of the prototypical inventive embodiment shown in **FIG. 4**.

FIG. 22 is a graphical representation of the required voltage of the actuators, in terms of volts versus frequency (Hz). This graph is based on voltage data which were obtained during inventive testing, using the demonstration test rig shown in **FIG. 17**, of the prototypical inventive embodiment shown in **FIG. 4**.

FIG. 23 is a diagrammatic top plan view, sans upper plate and partially in section, of an inventive embodiment having a peripherally situated annular actuator, a centrally situated sensor and a centrally situated streamlined resilient element (with diameter comparable to the length / width of the attachment plates).

FIG. 24 is a diagrammatic elevation view, partially in section, of the inventive embodiment shown in **FIG. 23**.

FIG. 25 is a diagrammatic top plan view, partially in section, of an

inventive embodiment similar to that shown in **FIG. 23** and **FIG. 24**, wherein the centrally situated streamlined resilient element is a complete (nonsegmented) torus.

FIG. 26 is a diagrammatic top plan view, partially in section, of an inventive embodiment similar to that shown in **FIG. 25**, wherein the centrally situated streamlined resilient element is noncircularly toroidal rather than circularly toroidal as shown in **FIG. 25**.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to **FIG. 1** through **FIG. 3**, constant natural frequency (CNF) passive-active mount **16** includes four peripherally situated cylindrical streamlined resilient CNF elements **17**, square upper plate-like member **18**, square lower plate-like member **19**, an inertia actuator (or "shaker") **20**, and a velocity sensor **22**. Actuator **20** and sensor **22** represent a collocated actuator-sensor pair; that is, actuator **20** and sensor **22** are coupled with plate **19** and are centrally located, collocatedly at center *c*. Streamlined resilient elements **17** are distributed about center *c*, perimetrically or peripherally in relation to each of plate members **18** and **19**.

Resilient elements **17** are shaped like short cylinders (disks), and are situated so that their circumferential surfaces are contacting, on opposite sides, the two plates **18** and **19**. More specifically, as regards each streamlined resilient element **17**, upper plate **18** has a lower surface **81** which contacts a surface portion of resilient element **17**, and lower plate **19** has an upper surface **91** which contacts a surface portion of resilient element **17**.

The CNF elements **17** have a "streamlined" shape characterizing

"constant natural frequency" elements, are attributed with flexibility or resiliency, and are made of an elastomeric or viscoelastic material. Inertia actuators **20** are mounted upon upper surface **91** of lower plate **19**. Velocity sensors **22** are mounted in blind tapped holes in lower plate **19** at virtually the same locations. Actuators **20** and sensors **22** are thus paired one-to-one, i.e., one actuator **20** correspondingly with respect to one sensor **22**. Inventive CNF mount **16** is installed between machinery **24** and foundation **26**.

Plates **18** and **19** can be made of metal and non-metallic materials (e.g. composites) provided with blind tapped holes (conventionally abbreviatedly referred to as "blind taps") and/or protruding bolts, not shown, which serve to facilitate attachment to other structures. Blind tap holes are attachment provisions, recessed in plates **18** and **19**, which are closed at the bottom until a bolt or stud is inserted for attachment purposes. The peripheral (perimetric) shapes of plates **18** and **19** can vary, depending on the application. For instance, plate **19** is shown in **FIG. 2** to be either rectangular or circular. Practically any peripheral plate shape, rectilinear and/or curvilinear (e.g., rectangle, circle, oval, polygon having any number of sides, etc.) is possible in inventive practice, but usually with the requisite that plates **18** and **19** each at least generally, at least approximately or at substantially define a plane.

According to some inventive embodiments, plates **18** and **19** are the original end closures or retainers themselves which are attached to resilient members **17**; according to other inventive embodiments, plates **18** and **19** are made to incorporate auxiliary plate-shaped members, coupled with the original retainer members, because the original retainer members are too small (e.g., diametrically) to effectuate a particular application. Although the term "mounting plates" has conventionally been used to denote such auxiliary plates used for mounting purposes, the term "plate" as used herein refers to any mount **16** end (or backing) plate which can be used for mounting purposes, including either an original retainer member or an auxiliary mounting member or some combination thereof.

Reference is now made to **FIG. 4** and **FIG. 5**, which each show a mount **16** arrangement similar to that shown in **FIG. 1** through **FIG. 3**. Notable are the distinguishable shapes of resilient elements **17** shown in **FIG. 1** through **FIG. 3**, vis-a-vis' those shown in **FIG. 4**, vis-a-vis' those shown in **FIG. 5**. The resilient elements **17** shown in **FIG. 1** through **FIG. 3** describe circular cylindrical (more specifically, disk) shapes. The resilient elements **17** shown in **FIG. 4** are somewhat prolate, in comparison with the circular disk shapes shown in **FIG. 1**, so as to describe oval or oblong cylindrical (more specifically, disk) shapes. The resilient elements **17** shown in **FIG. 5** are shaped like "donut segments."

As shown in **FIG. 1** through **FIG. 5**, a single sensor **22** and a single actuator **20** are collocatedly paired. Reference is now also made to **FIG. 6** through **FIG. 8**, wherein plural sensors **22** and plural actuators **20** are shown in each figure. Typically according to this invention, regardless of the numbers of sensors **22** and actuators **20**, sensors **22** and actuators **20** are collocatedly paired. For each collocation the sensing of the sensor **22** and the actuation of the actuator **20** are approximately in the same, generally vertical, direction indicated by directional arrow ***d***. If there are plural collocations, such as shown in **FIG. 6** through **FIG. 8**, all of the collocational directions ***d*** (such as shown in **FIG. 3**) are approximately parallel. Mount **16** can be envisioned to have a vertical axis of symmetry, such as represented by dashed line ***a*** in **FIG. 3**, through plates **18** and **19**. Imaginary axis ***a*** is approximately parallel to every collocational direction ***d*** and passes through center ***c*** of lower plate **16**.

In **FIG. 6** and **FIG. 7**, actuators **20** and co-located sensors **22** are seen to be symmetrically distributed with respect to center ***c***. In arrangements such as depicted in each of **FIG. 6** and **FIG. 7**, one resilient element **17** is positioned at center ***c***. The single, central resilient element **17** can have any suitable shape, such as the circular cylinder or spherical shape shown in **FIG. 6**, or the circular disk shape shown in **FIG. 7**, or the oval cylinder or prolate spheroidal shape shown in **FIG. 8** (streamlined

resilient element **17P**). Any number of plural (e.g., two or four) actuators **20** and any corresponding number of plural (e.g., two or four) co-located sensors **22** are collocationally positioned in a symmetrical arrangement about center *c*.

According to frequent inventive practice, the streamlined resilient element(s) **17** and the collocated actuator **20**/sensor **22** pair(s) are symmetrically distributed about center **c** (or vertical axis **a**) in both the "x" and "y" directions in an imaginary horizontal plane which is perpendicular to vertical axis **a**. **FIG. 6** through **FIG. 8** suggest the possibility that, in accordance with inventive principles, the streamlined resilient element(s) **17** and the collocated actuator **20**/sensor **22** pair(s) be nonsymmetrically arranged about center **c** (or vertical axis **a**), or that they be arranged symmetrically in only one direction in the imaginary horizontal plane (i.e., either the "x" direction or the "y" direction). **FIG. 8** also portrays the inventive utilization of plural kinds of shapes of streamlined resilient elements **17** within the same inventive mount **16**. The present invention's mount **16** admits of a variety of possible combinations of elements **17** in terms of their shapes.

A truncated streamlined resilient element is provided with at least one truncation surface **21**. Again referring to **FIG. 4** and also referring to **FIG. 9** and **FIG. 10**, truncated streamlined resilient elements **17** are each

provided with two opposite, approximately parallel and approximately flat (planar) truncation surfaces **21a** and **21b**. The top (upper) truncation surface **21a** of streamlined resilient element **17** is adaptable to attachment to top (upper) plate **18** whereby top truncation surface **21a** abuts the bottom (lower) surface **81** of upper plate **18**. Similarly, the bottom (lower) truncation surface **21a** of streamlined resilient element **17** is adaptable to attachment to bottom (lower) plate **19** whereby bottom truncation surface **21a** abuts the top (upper) surface **91** of lower plate **19**. Truncation surfaces **21** are also shown "edgewise" in **FIG. 8** and **FIG. 11** through **FIG. 14**. Generally in accordance with the present invention, a streamlined resilient element **17** can be (i) totally nontruncated, or (ii) truncated on one of its opposite ends or sides, or (iii) truncated on both of its opposite ends or sides.

As illustrated in **FIG. 4**, when inventive mount **16** is completely assembled, segmented torus-shaped streamlined resilient element **17** is disposed "sideways" so that its upper truncation surface **21a** is adjacent to the lower surface **81** of upper plate **18**, its lower truncation surface **21b** is adjacent to the upper surface **91** of lower plate **19**, and the imaginary longitudinal axis defined thereby approximately is equidistant between and parallel to the upper plate **18** lower surface **81** and the lower plate **19** upper surface **91**. This inventive dispositional approach regarding

streamlined resilient element **17**, wherein the element **17** is laid sideways upon the lower plate **19** and is "sandwiched" between upper plate **18** and lower plate **19**, similarly applies to segmented torus-shaped elements **17** (wherein the imaginary axis defined by element **17** is curved within an imaginary horizontal plane) as well as cylindrical elements **17** (wherein the imaginary axis defined by element **17** is straight within an imaginary horizontal plane). It is noted that segmented torus-shaped element **17** (shown in **FIG. 9**) and cylindrical section-shaped element **17** (shown in **FIG. 10**) can each have either a round (circular or oval) profile.

With reference to **FIG. 11** through **FIG. 14**, usually according to this invention a streamlined resilient element **17** will define one of three basic profiles, viz., circular, non-circular vertically elongated or non-circular horizontally elongated. Each figure shows a representative profile (cross-sectional shape). In the light of this disclosure, it will be understood by the ordinarily skilled artisan that each streamlined resilient element **17** profile can represent either a "three-dimensional" curvilinear form (i.e., a form having a three-dimensional axis of symmetry, e.g., a sphere or prolate spheroid) or a "two-dimensional" curvilinear form (i.e., a form having a two-dimensional axis of symmetry, e.g., a circular-profile cylindrical section, an oval profile cylindrical section, a circular-profile torus segment or an oval profile torus segment). A "disk" is a cylinder (cylindrical section)

wherein the cylinder's longitudinal axis is "short" relative to the cylinder's width or diameter.

The profile shown in **FIG. 11** and **FIG. 14** is circular; the profiles shown in **FIG. 12** and **FIG. 13** are noncircular. **FIG. 11** and **FIG. 14** each represent a streamlined resilient element **17** which is a sphere or a circular cylinder (e.g., a circular disk) or a circular torus segment. **FIG. 12** and **FIG. 13** each represent a streamlined resilient element **17** which is a prolate spheroid or an oval cylinder (e.g., an oval disk) or an oval torus segment. The streamlined resilient element **17** which is shown in **FIG. 12** is adaptable to joining endplates **18** and **19** along its length; the streamlined resilient element **17** which is shown in **FIG. 13** is adaptable to joining endplates **18** and **19** along its width.

Notable is the possible variation, in terms of non-truncation or degrees of truncation, within a given streamlined resilient element **17** shape. In each of **FIG. 11** through **FIG. 14**, a non-truncated streamlined resilient element **17** version (streamlined resilient element **17_1**) of streamlined resilient element **17** is completely representative of the form described thereby, whereas a truncated streamlined resilient element **17** version (streamlined resilient element **17_2**) is substantially representative of the form described thereby. The truncation can be provided at either or both ends of streamlined resilient element **17**. Streamlined resilient

element **17_2** shown in **FIG. 14** is truncated at the bottom end and nontruncated otherwise. If both ends of an element **17** are truncated, such truncations can differ in degree. A given element **17** can range from being entirely non-truncated to being (at either or both ends) moderately truncated to being more severely truncated.

With reference to **FIG. 15**, for each feedback loop subsystem, a sensor is responsive to local vibration, the PID-type controller is responsive to that sensor's signal, and that sensor's companion actuator is responsive to the controller's signal. Sensor **22** is connected to an input channel **28** of PID-type controller **30**. Sensor **22** responds to the localized vibration of lower plate **19** by sending a sensor signal to PID-type controller **30**. Actuator **20** has a power system **34** which is connected to an output channel **32** of PID-type controller **30**. PID-type controller **30** responds to the sensor signal by sending a control signal to actuator **20**. Output channel **32** is connected to the power system **34** of the actuator **20** which is collocated with and companion to that particular sensor **22**. Actuator **20** responds to the control signal of PID-type controller **30** by exerting a vibratory force upon the lower plate **19** locality. Power cord **36** is "plugged into" an ac outlet, in a manner which is conventional for electronic equipment. Knob **38** of controller **30** is used for manually adjusting performance of the particular active control subsystem.

For example, an inventive vibration isolation system embodiment which includes an inventive mount embodiment such as shown in **FI6. 6**, **FIG. 7** or **FIG. 8** can be envisioned. Each one of plural (e.g., two or four) sensors **22** is connected to a corresponding one of plural (e.g., two, three or four) input channels **28**, and the collocated one of plural (e.g., two or four) actuators **20** uses a power system **34** connected to all of the (e.g., both, all three or all four) output channels **32**. As another example, an inventive vibration isolation system embodiment which includes an inventive mount embodiment such as shown in **FI6. 1** through **FIG. 5** would be characterized by the connection of a single sensor **22** to a single input channel **28**, and by the utilization by the single collocated actuator **20** of a power system **34** which is connected to a single output channel **32**.

Controller **30** as depicted in **FIG. 15** has one control knob **38** which is for adjustment of the performance, based on frequency response, for one or more sensors of a particular inventive embodiment, e.g., sensors **22** of inventive mount (spring assembly) **16**. In inventive practice, the processor/controller can implement one or more control knobs or dials, manually operated for modulation purposes. Each knob **38** is tuned by the operator for performance, the performance being realized by the frequency response of the corresponding sensor or sensors **22**. A frequency response indicator or display device for each sensor **22** can be designed and built

into inventive mount **16**, or can be otherwise conveniently located, e.g., below, next to or near inventive mount **16**.

For many inventive embodiments, use of a single knob **38** for collective adjustment facilitates operation; it may be pragmatic that a single knob **38** be implemented for a plurality of sensors **22**, or even for the entire group of sensors **22** for a given application, because the sacrifice in terms of tuning "fineness" is secondary to the gain in terms of ease of operation. Alternatively, each sensor **22** can have corresponding thereto its own knob **38**; for example, as regards inventive mount **16** such as shown in **FIG. 6** or **FIG. 7**, controller **30** can be envisioned to have plural (e.g., four) knobs **38**, each knob **38** corresponding to one sensor **22** for inventive mount **16**.

Sensors **22** are preferably velocity sensors **22** for many embodiments of this invention, wherein simple velocity feedback can thus be effectuated. Some inventive embodiments preferably employ sensors **22** which are accelerometers **22**. Incorporated herein by reference are the following two United States patents, viz., to Geohegan, Jr. et al. at U.S. Patent 4,083,433, and to Phillips et al. at U.S. Patent 4,922,159. Geohegan, Jr. et al. are instructive regarding active vibration control based on sensing of vibration velocity, and Phillips et al. are instructive regarding active vibration control based on sensing of vibration acceleration.

Conventional passive mounts work on the principle of low dynamic load transmissibility by virtue of their resilient material property. They are designated "passive" because their function is based on their inherent property instead of their ability to react to the in-situ condition. A conventional passive vibration isolation mount is not as effective as one might expect for a practical foundation having resonant frequencies within the bandwidth of interest. Moreover, low frequency enhancement is a characteristic of conventional passive mounts; due to their inherent low frequency resonance, conventional passive mounts may be ineffective or may even cause enhancement of dynamic load transmission at low frequency. On the other hand, in the case of active load transmissibility control, a much higher local impedance is created by an actuator which can be very effective with proper controller design but which suffers from limited mechanical response at high frequency. The present invention uniquely blends "the best of both worlds," so to speak, namely the passive vibration control realm and the active vibration control realm, so as to complement each other in terms of obviation of each other's weaknesses as well as overall vibration suppression effectiveness.

An inventive CNF passive-active mount **16**, wherein one or more inertia actuators **20** are applied to lower attachment plate **19**, not only can remedy problems associated with a realistic foundation but can also

enhance performance so that it exceeds what performance would be on an ideal rigid foundation. Many inventive embodiments preferably use collocated velocity feedback, which is the simplest and perhaps most widely used vibration suppression algorithm. The controller design for the inertia actuators pursuant to collocated velocity feedback is uncomplicated. The collocated velocity feedback design concept has universal application; it is applicable to any dynamic system. Additionally, the required actuator force is typically undemanding for an inventive CNF passive-active mount. An inventive CNF passive-active mount generally requires very little power and force capacity from the actuators -- i.e., a small percentage of the disturbance force above the mount -- in order to be effective for frequencies higher than the resonant frequency of the mount itself. Furthermore, for small-scale machinery or delicate equipment, the low frequency enhancement can also be reduced, if desired, since the required actuator output force capacity is within the hardware limitation.

Generally, when an inventive CNF passive-active mount is oriented vertically such as generally depicted in **FIG. 1** through **FIG. 8**, its passive vibration isolation mode will inherently provide better vibration isolation in transverse (i.e., horizontal) directions than in axial (i.e., vertical) directions, since the transverse spring rate normally will be lower than the axial spring rate. Hence, normally in inventive practice, lateral stability of

the mounted object will be of greater concern than the degree or sufficiency of transverse vibration isolation. Nevertheless, for some inventive embodiments, the requirements or specifications may be so stringent as to demand even better transverse vibration isolation than is intrinsically passively provided by the inventive resilient CNF mount. If such is the case, for example, an inventive CNF passive-active mount can be oriented horizontally and situated between an object and a vertical restraining member. For instance, each inventive CNF passive active mount **16** represented in the figures can be envisioned to be is oriented horizontally and situated between machinery **24** and foundation **26**. For instance, each inventive mount **16** can be oriented horizontally and situated between a vertical surface of machinery **24** and a vertical component of a bracket, wherein the horizontal component of the bracket is attached to horizontal foundation **26**, and the vertical component of the bracket is attached to the mount's vertical lower plate **19**.

As another example, vertically oriented inventive CNF passive-active mount **16** can include one or more collocated pairs of sensors **22** and actuators **20** whereby the collocatedly paired sensing and actuating functions are approximately in the same transverse direction, such as indicated by directional arrow ***t*** in **FIG. 2** and **FIG. 3**. For instance, inventive mount **16** can be envisioned in **FIG. 2** and **FIG. 3** to have: one

or more (e.g., two opposite) perimetric collocated sensor **22**-actuator **20** pairs having a first transverse direction t_1; and/or, one or more (e.g., two opposite) perimetric collocated sensor **22**/actuator **20** pairs having a second transverse direction t_2 which is orthogonal with respect to first transverse direction t_1; and/or, one or more (e.g., two opposite) central collocated sensor **22**-actuator **20** pairs having axial direction d which is orthogonal with respect to both first transverse direction t_1 and second transverse direction t_2.

Alternatively, inventive CNF passive-active mount **16** can be envisioned to include one or more triaxial sensor-actuator units. Each triaxial unit has three collocated sensor **22**-actuator **20** pairs oriented in three orthogonal directions, e.g., two transverse directions and an axial direction. That is, in Cartesian space, a first orthogonal direction is along or parallel to the x axis, a second orthogonal direction is along or parallel to the y axis, and a third orthogonal direction is along or parallel to the z axis. In the light of the teachings herein, practice of an inventive CNF passive-active mount **16** so as to be instrumented with one or more such triaxial units **42** should be within the capability of the ordinarily skilled artisan. Triaxial sensors are commercially available; triaxial actuators have been custom-designed, e.g., for industrial plants, and can be specially ordered from manufacturers.

Diverse integrated designs of inventive mount **16**, in terms of kinds and arrangements of the passive and active components, are possible in accordance with the present invention. As portrayed in **FIG. 1** and **FIG. 4**, which are conceptually similar, four "short" element **17** cylinders (alternatively referred to as "disks") of resilient material are located on four sides of CNF mount **16** so as to surround a lower profile (less tall) inertial actuator **20** which is located at the center **c**. The prototype CNF mount **16** design shown in **FIG. 4** was fabricated for conducting the physical test demonstration of the present invention.

Referring to **FIG. 16**, depending on the material, thickness and diameter of the short element **17** cylinders, the mount **16** stiffness varies. Several combinations of these design parameters were fabricated. The respective load-deflection curves of the different mount **16** designs are shown in **FIG. 16**, wherein the legend indicates, in order: the diameter of each element **17**; the thickness of each element **17**; and, the durometer number of the natural rubber of which each element **17** was made.

As shown in **FIG. 16**, the load-deflection curves are for the calculation of the compression stiffness. For the prototype design, the combination of design parameters of 2.5"/0.75"/40 (diameter/thickness/Durometer Shore A) was chosen; the curve pertaining thereto has about the medium stiffness and provides a mount frequency at

around 10 Hz regardless of the isolation weight. This constancy of frequency regardless of the isolation weight represents an important feature of the present invention's CNF design concept. The shear or lateral stiffness was not measured; however, it could be estimated to be at least one order lower because of the much greater flexibility which could be felt by hand. Consequently, the present invention's CNF mount **16** decouples the shear vibration from the compression vibration, thereby achieving superior passive isolation effect in the shear direction and eliminating the need for the active component in the shear direction.

FIG. 16 shows the curves which were used, pursuant to inventive testing, to obtain the suitable stiffness(es) for the particular inventive CNF mount design(s) being tested. In theory, the present invention's CNF passive-active mount is supposed to demonstrate an upward bending of each load-deflection curve, indicating in increase in stiffness as the load is increased, thereby achieving the "constant natural frequency," which represents the ratio of the stiffness to the load (or, synonymously, the weight). However, this behavior is not illustrated entirely clearly in **FIG. 16**, because the load range is not large enough. The load-deflection curve's behavior of bending upward is more pronounced if the load range is greater. Since the data collected pursuant to inventive testing was intended to demonstrate the performance of particular inventive CNF

passive-active mounts, the testers did not bother to increase the load level beyond what they designed for the demonstration. Nevertheless, the reader's attention is directed to the "softer" curves (e.g., the star symbol curve representing 2.25"/0.75"/50 and the solid line curve representing 2.5"/0.50"/30) in **FIG. 16**, wherein this trend of bending upward is more readily observed. As previously noted herein, according to typical inventive embodiments, the significant range of loading corresponding to natural frequency constancy is between a minimum degree of loading and a maximum degree of loading, wherein the maximum degree of loading is no less than about ten times the minimum degree of loading, and wherein the maximum degree of loading is no more than about one hundred times the minimum degree of loading.

With reference to **FIG. 17**, a demonstration test was conducted of the present invention's CNF passive-active prototype mount **16** shown in **FIG. 4**. In furtherance of a hardware demonstration of the performance of the present invention's CNF passive-active mounts, a simple test rig was designed and fabricated as follows: A machine **24** (mass block of 6 inches by 3 inches by 14.75 inches) weighing 75 pounds, with its largest dimension of 14.75 inches in the axial direction, was mounted onto a cantilever T-beam **26** by two CNF passive-active mounts **16**$_a$ and **16**$_b$ at both ends, as shown in **FIG. 17**. The cantilever beam **26** was made of steel

of "T" cross-section (WT 3x10) weighing 24.5 pounds with a length of 29.125 inches. The mass block **24** was located in the middle of the steel beam **26** span; that is, the mid-span of mass block **24** was at the mid-span of T-beam **26** along the length. This cantilever beam **26** was the elastic machinery foundation, having a structural loss factor of 1 percent and a mass ratio (machinery/foundation) of about 3.0. T-beam **26** had the first fundamental frequency of 93 Hz and a second 485 Hz in bending and the first longitudinal resonance frequency at 1703 Hz.

The passive component (streamlined resilient element) **17** of the CNF passive-active mount was made of natural rubber with a nominal loss factor of 0.1. Depending on the design of passive component **17** -- for example, the shape factor and the geometric parameters (e.g., diameter, hardness and thickness of the short cylindrical elements **17**) -- the compression mount frequency for this particular design was about 10 Hz. For the active component, a MOTRAN brand inertial actuator **20** and an accelerometer **22** in its vicinity formed a "collocated" actuator/sensor pair in the perpendicular direction to the mounting surface **92** of T-beam **26**. In this demonstration, the actuator command signal was controlled by the negative velocity feedback with a constant gain. The manufacturer of inertial actuator **20** was Motran Industries, Inc., 25570 Rye Canyon Road, Unit J, Valencia, California, 91355.

Reference is now made to **FIG. 18** through **FIG. 22**. With the disturbance force applied from the shaker **25** on top of the block mass **24** in the vertical direction, the responses below each of inventive CNF passive-active mount **16**$_a$ and **16**$_b$ in the vertical direction of the cantilever beam **26** were measured. Both the acceleration responses to the passive component only of the inventive CNF passive-active mounts **16** and the normal operation of the inventive CNF passive-active mounts **16** in the frequency up to 1000 Hz were recorded for comparison.

The acceleration below mount **16**$_a$ (the mount **16** located closer to the foundation support **27**, i.e., closer to the fixed end of T-beam **26**) is shown in **FIG. 19**, subject to the vertical disturbance force from the shaker as shown in **FIG. 18**. Since the velocity feedback gain was moderate, the inertial actuator **20** in this mount simply worked as an efficient broadband vibration damper, thus representing the function of the inertial actuator **20** in the inventive CNF passive-active mount. This is also shown in **FIG. 20** for mount **16**$_b$ (the mount located further from the foundation support **27**, i.e., closer to the free end of T-beam **26**). The mounting location for mount **16**$_b$ (the location closer to the free end of T-beam **26**) had lower impedance than did the mounting location for mount **16**$_a$ (the location closer to the fixed end of T-beam **26**); therefore, mount **16**$_b$ (located closer to the free end of T-beam **26**) had greater response than did mount **16**$_a$

(located closer to the fixed end of T-beam **26**) by about 7 dB.

As shown in **FIG. 21**, the measured actuator **20** current at mount **16**$_a$ (located closer to the free end of T-beam **26**) was, in general, smaller than the measured actuator **20** current at mount **16**$_b$ (located closer to the free end of T-beam **26**). This is mainly due to the smaller gain used for the actuator closer to the free end. This was also true for the measured actuator **20** voltage, as shown in **FIG. 22**. The levels of current and voltage used in this demonstration were less than 3 percent of the rated capacity of this particular model of the MOTRAN actuator.

It is recalled that some inventive embodiments provide a centrally located streamlined resilient element **17** and peripherally located plural actuators surrounding element **17**, such as shown in **FIG. 6**. Now referring to **FIG. 23** through **FIG. 26**, it may be preferable to adopt a different inventive configuration when the passive components (element or elements **17**) are centrally located. As shown in **FIG. 23** through **FIG. 26**, rather than placing plural separate actuators **20** around the central element(s) **17**, instead a single annular actuator ("ring-actuator") **20** can be placed around the central element(s) **17**.

FIG. 5 is illustrative of the advantageousness of using plural, discrete, peripherally situated torus-segment shaped elements **17**, as distinguished from using a single peripherally situated torus-shaped

element **17** which can be envisioned based on **FIG. 5**. A single peripheral torroidal element **17** would tend to generate excessive heat, or impede the dissipation of excessive heat. In fact, the prevention of such excessive heat is an underlying principle for the preference of using plural discrete streamlined resilient elements **17** about the periphery, since the spaces in between the elements **17** encourage escape or attenuation of unwanted heat. Hence, the implementation of a torus-shaped element **17** is possible according to this invention, but thermal considerations should not be overlooked. A relatively small, centrally located torus-shaped element **17**, such as shown in **FIG. 25**, would probably avoid or minimize such heat-related problems.

As shown in **FIG. 5**, the four congruent segmentedly toroidal elements **17** define a circular shape in the imaginary horizontal geometric plane passing therethrough. Similarly, as shown in **FIG. 25**, the single toroidal element **17** defines a circular shape in the imaginary horizontal geometric plane passing therethrough. As shown in **FIG. 26**, inventive practice also permits noncircular (oval, e.g., elliptical) planar configurations of a complete toroidal element **17** or of a plurality of toroidal segment elements **17s**. In this regard, ring-shaped actuator **20** and planarly round sensor **22** can each be characterized by either a circular planar shape (such as shown in **FIG. 25**) or a noncircular planar shape

(such as shown in **FIG. 26**). Note that practically any plural number of segmented torus-shaped streamlined resilient elements, such as elements **17s** shown in **FIG. 26**, can be implemented in accordance with the present invention. Moreover, such segmented torus-shaped elements can be similar or dissimilar in size and/or shape, and in various combinations.

Other embodiments of this invention will be apparent to those skilled in the art from a consideration of this specification or practice of the invention disclosed herein. Various omissions, modifications and changes to the principles described may be made by one skilled in the art without departing from the true scope and spirit of the invention which is indicated by the following claims.